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Experimental and Numerical Study of Enlarged-Head Monopile Under Lateral Load in Soft Clay

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Abstract

The behavior of piles and the reaction of soils in contact with structures are crucial aspects of foundation engineering. Laboratory model tests were investigated to evaluate the enhancement of the subgrade modulus for laterally loaded piles with enlarged heads in clay. These tests compared typical piles with enlarged heads in soft clay, considering factors such as the pile slenderness ratio and geometric configurations. The study was expanded by simulating monopiles with and without head enlargements using the numerical program Plaxis 3D. The results highlight the effectiveness of enlarged-head piles, demonstrating a substantial increase in lateral subgrade reaction with adequate head depth. For piles with Lp/Dp = 24, an enlarged head geometry of Le/Lp = 0.4, Δ De/Dp = 1, and an undrained shear strength Cu = 15, the subgrade modulus improved by 200% compared to typical piles. Additionally, for Lp/Dp = 24 piles, the improvement due to enlargement was 1.3 and 2 times for Cu values of 10 and 15 kPa, respectively. These findings emphasize the advantages of using enlarged heads, especially uniform shapes, which are more practical and effective than tapered shapes. The numerical simulations corroborated the experimental results, providing detailed insights into deformation and bending moment variations that are challenging to measure in laboratory tests.

Keywords: Soil-Pile Interaction; Winkler Modulus; Soft Clay; Enlarged Piles; Lateral Load; Plaxis 3D.

1. Introduction

High-rise buildings, transmission towers, masts, and offshore platforms include structures that are subject to lateral forces brought on by wind, waves, seismic activity, and ship collisions. Therefore, in deep foundation design, the lateral load capability of piles is crucial since too much deflection might cause failure. Many approaches have been devised for examining how piles and pile groups behave when subjected to lateral loads. The type of applied load, soil properties, and pile shape all affect a pile's lateral capacity. Either the near-surface soil characteristics or the pile design, such as employing tapered, helical, or finned piles, can be modified to increase this capacity. Several methods to improve the lateral performance of piles or pile groups under these circumstances have been investigated in several research studies.

The bearing characteristics of Y-shaped piles in saturated sand were examined by Ren et al. [1]. Y-shaped piles were used in model tests under both compressive and horizontal loads. According to the findings, the direction of the applied load affects the lateral bearing capacity of Y-shaped piles. Additionally, while converting a circular section into a Y-shaped one can increase the horizontal bearing capacity for the same amount of concrete, the additional

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surface area is not fully utilized to enhance the horizontal bearing capacity in saturated sand. Similarly, finned piles in sand were also investigated by Qin et al. [2] under static lateral stresses. Comparing finned piles to control piles, the results showed a considerable increase in lateral stiffness and load capacity. The increases for diameters of 38.1 mm, 25.4 mm, and 19 mm were 207%, 146%, and 32%, respectively.

Yang et al. [3] used FELA and theoretical analysis to investigate the impact of cement-enhanced soil on the lateral resistance of clay composite piles. The results showed that strengthening the soil led to an increase in the ultimate lateral resistance factor (NP) by 6.2% to 232.6%. However, no significant change was observed when the strength of the improved soil exceeded eight times that of the natural soil. In addition, Islam et al. [4] examined the performance of single and group PHC piles in soil improved with cement. The findings showed that the use of cement-enhanced soil improved pile performance, reducing the bending moment and head displacement by up to 25% and 45% for single piles, and by 47% and 24% for group piles, respectively. In a similar context, Hariswaran et al. [5] employed the PLAXIS 3D finite element analysis program to study the behavior of a laterally loaded defective (necking) pile with fins surrounding it. The results confirmed that the lateral load-carrying capacity of the fin-encased defective pile is enhanced up to the top third of the pile.

Jegadeesh Kumar et al. [6] investigated the performance of conventional monopiles compared to laterally loaded rigid helical piles on sloped ground. In particular, helical piles outperformed monopiles on sloping surfaces, as evidenced by their 100% increase in uplift resistance and 53% improvement in lateral resistance. In addition, the effect of simultaneous torsional and lateral stresses on finned shaft piles in sandy soil was investigated by Sallam et al. [7]. The study examined 45 experimental test findings on shaft piles' combined lateral and torsional capacities in dry sand, both with and without pile head expansion. The findings demonstrated that as the fin width-to-pile diameter ratio increases, finned piles' ability to resist combined torsional and lateral loads improves. Similarly, the experimental and computational analysis of RCC (Reinforced Concrete) piles with helical grooves under axial and lateral stresses in cohesionless soil was conducted by Kumar et al. [8]. As compared to the control pile, RCC piles with a 50 mm helical groove pitch showed a significant 158% improvement in axial load-carrying capacity when examined using a 10% settling criterion.

Existing literature predominantly focuses on experimental and numerical approaches to enhance lateral pile capacity, often overlooking their effect on the subgrade reaction around the pile head. This paper aims to define, establish, and evaluate the relationship between subgrade improvements and various configurations of enlarged piles. Specifically, the study explores the variations and enhancements in the soil subgrade reaction "K" relative to the un-drained shear strength of the clay and the slenderness ratio of the model piles, both with and without enlarged heads. Additionally, finite element analysis is used to validate the experimental model test, providing deeper insights into deformation responses and bending moments that may not be fully captured through laboratory experiments. Figure 1 illustrates the flowchart for this methodology.

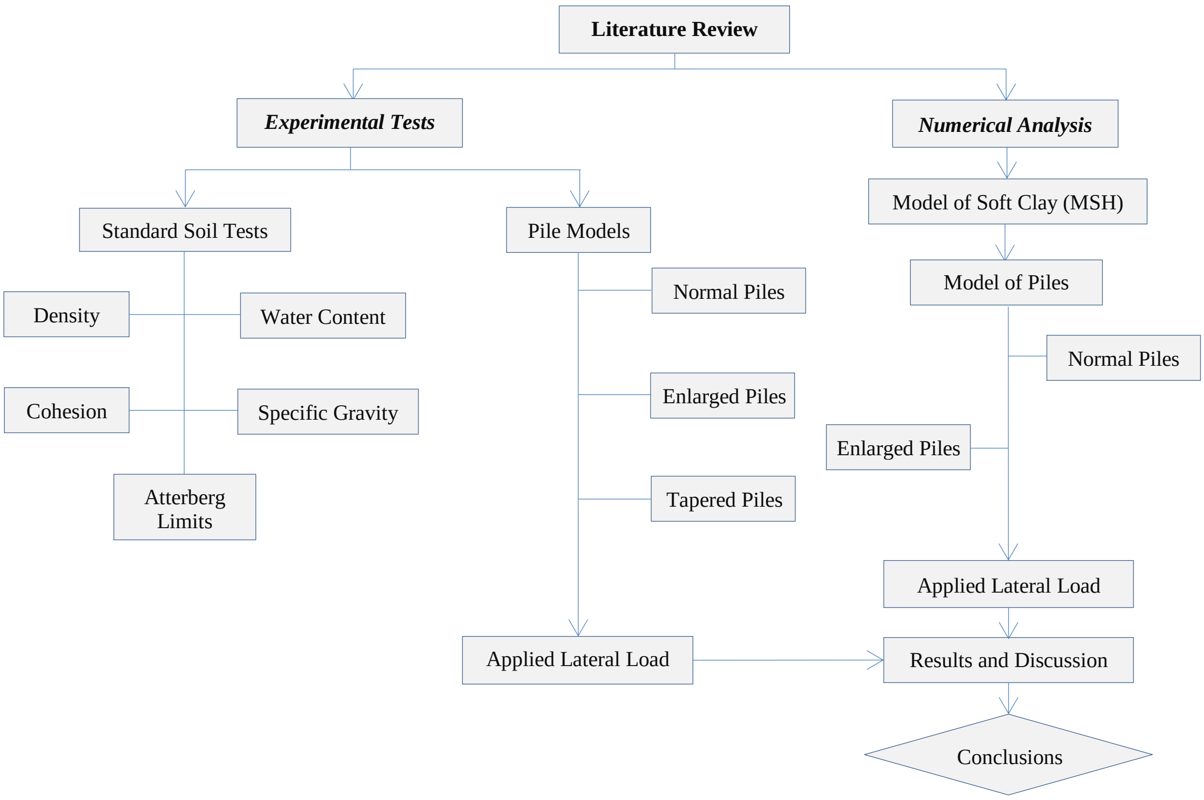


Figure 1. Flowchart for study methodology

2. Experimental Model and Materials

The small-scale laboratory tests were done in a testing model that has been fabricated especially for exerting lateral loads on the pile top head. Figure 2 shows a schematic diagram of the testing equipment. The testing setup includes four main parts, which are a steel tank combined with a loading system, model piles, and surrounding soil. However, the experiment is in sequence, as described in the following main parts:

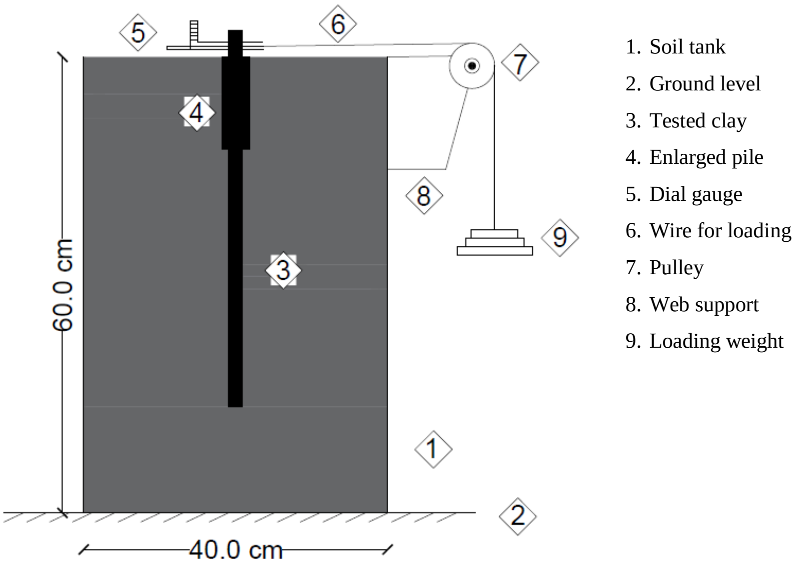


Figure 2. Layout of testing equipment

2.1. The Test Tank

The testing setup consisted of a mild steel tank with four welded sides, each made of 2.5 mm thick plates, and a 5 mm thick base plate, designed to prevent any lateral deformation of the tank's sides. The tank's dimensions were 400 mm in width, 400 mm in length, and 600 mm in depth. The inner surface of the tank was marked at 50 mm intervals to ensure the proper formation of the soil during testing. In this study, the tank dimensions were carefully chosen to minimize the influence of scale effects and boundary conditions on the test results by the methods outlined by Meyerhof [9], Robinsky & Morrison [10], Turner & Kulhawy [11], Al-Mhaidib [12], and Fatahi et al. [13].

To minimize friction, a soft, flexible, lubricated pulley system was mounted on the tank's sidewall. A steel tension wire, 4 mm in height and positioned horizontally above the soil surface, was used to apply lateral loads. One end of the wire was connected to a static weight, while the other end was secured to the center of the pile cap to ensure even load distribution. The weights applied lateral forces to the piles, as illustrated in Figure 2. The lateral displacement of the piles under each load was accurately measured using a digital settlement dial gauge with a precision of 0.01 mm, and the readings were recorded. Loads were applied incrementally at a constant value until pile deformation occurred.

2.2. Soil Model Description

Experiments were conducted on kaolin clay samples to assess their primary physical properties. The kaolin clay was procured from El Basatin for Industry in Cairo, Egypt. Laboratory preparation of the soil specimens involved mixing kaolin as described in previous studies [14-16].

To achieve the target density and cohesion, kaolin was mixed with water at predetermined contents of 45% and 35%. Two sets of soil specimens were prepared for the experimental design, each with different initial water contents. Tests were performed at average cohesion levels of 10 kPa and 15 kPa and the cohesion of the samples was verified using the vane shear test. The distribution of silt and clay particles was measured using a hydrometer, as presented in Figure 3.

The results revealed that 93.5% of the material passed through a No. 200 sieve, with the clay fraction accounting for 50% and the silt fraction for 43.5%, based on MIT classification. Table 1 presents the geotechnical properties of the tested clay, including slurry density, water content, Atterberg limits, specific gravity, and undrained shear strength. According to the Unified Soil Classification System (USCS), the soil sample was classified as CL, representing clay with low plasticity.

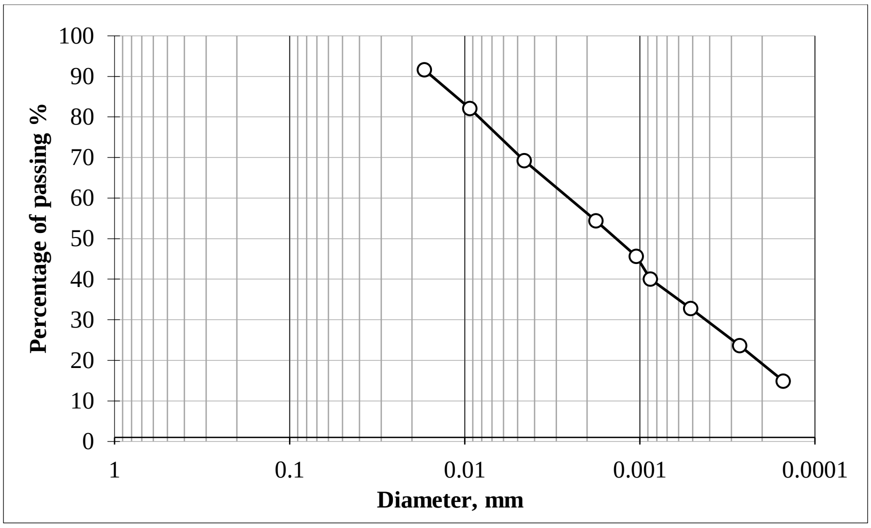


Figure 3. Grain size distribution curve from hydrometer test

Table 1. The Kaolin's properties as a soft clay

Physical properties	Very soft clay	Soft clay
Water Content	45%	35%
Density kN/m^3	17.5	18
Cohesion (Cu) kPa	10	15
Liquid limit (L.L)	30%	
Plastic limit (P.L)	15%	
Plasticity index (Ip)	15%	
Specific Gravity (Gs)	2.7	

2.3. Tested Model Piles and Head Enlargement

In this study, steel alloy pipe model piles with closed ends were used. These model piles had an external diameter of 25 mm, a wall thickness of 3 mm, and an inner diameter of 19 mm. The pile lengths were set at 300 mm and 600 mm, corresponding to length-to-diameter (L/D) ratios of 12 and 24, respectively. This setup was designed to assess pile performance under varying rigidity and slenderness ratios, as noted by Azzam & Elwakil [17]. To enhance the performance of the piles, enlarged heads were fabricated by welding steel pipes larger than the pile diameter of 25 mm, maintaining the same thickness as the normal piles. These enlarged heads were rigidly attached to the original piles, varying in diameter and depth, and positioned below the soil surface of the embedded pile, as illustrated in Figure 4. Various geometric dimensions and shapes of pile heads were examined to understand the effect of modification enlargement on enhancing pile behavior, as depicted in Figure 5. The tested piles with different head modifications, including uniform enlargement and inverted conical enlargement as tapered enlarged heads, were compared with normal piles.

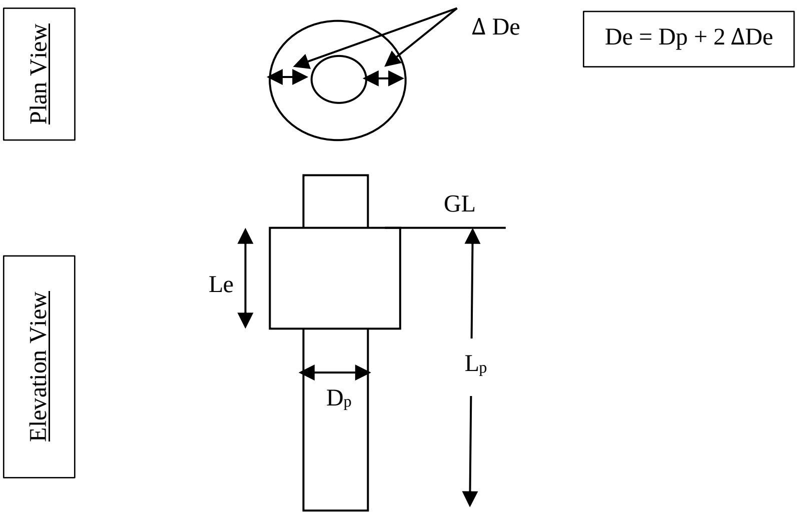


Figure 4. Model of the modified enlarged pile

(a) (b) (c)

Figure 5. Pile models with different modifications on the top head: a: normal pile; b: uniform enlargement; c: conical, tapered enlargement

A solid plate pile cap, with an outer diameter matching that of the pile, was attached to the top of each model pile. This arrangement facilitated the installation of the dial gauge and measurement of pile displacement, following the methods described by Albusoda & Alsaddi (2017) [18, 19].

2.4. Preparation of the Clay Bed and Installation Steps

This paper conducted two series of tests, as detailed in Table 2. In the first series, the clay was very soft with a shear strength of 10 kPa, while in the second series, the clay was relatively soft with a shear strength of 15 kPa. The same experimental procedure was followed for both series.

Initially, the inner sides and bottom of the tank were lined with plastic to prevent water seepage from the slurry and maintain its consistency. Kaolin was mixed to achieve the specified water content for each test series using a mechanical mixer for 20 minutes until the desired shear strength was attained. During the mixing process, the blender inspected the mixing quality, ensuring the slurry was free of lumps or clumps. The clay was added to the tank in 50 mm thick layers until it reached the pile tip. Figure 6 illustrates the laboratory apparatus and experimental setup for the model enlarged pile. Each layer was manually tamped and subsequently compressed using a special rammer to eliminate any air voids, by the methods described by Rao & Prasad [20], Basack [21] and Chandrasekaran et al. [22].

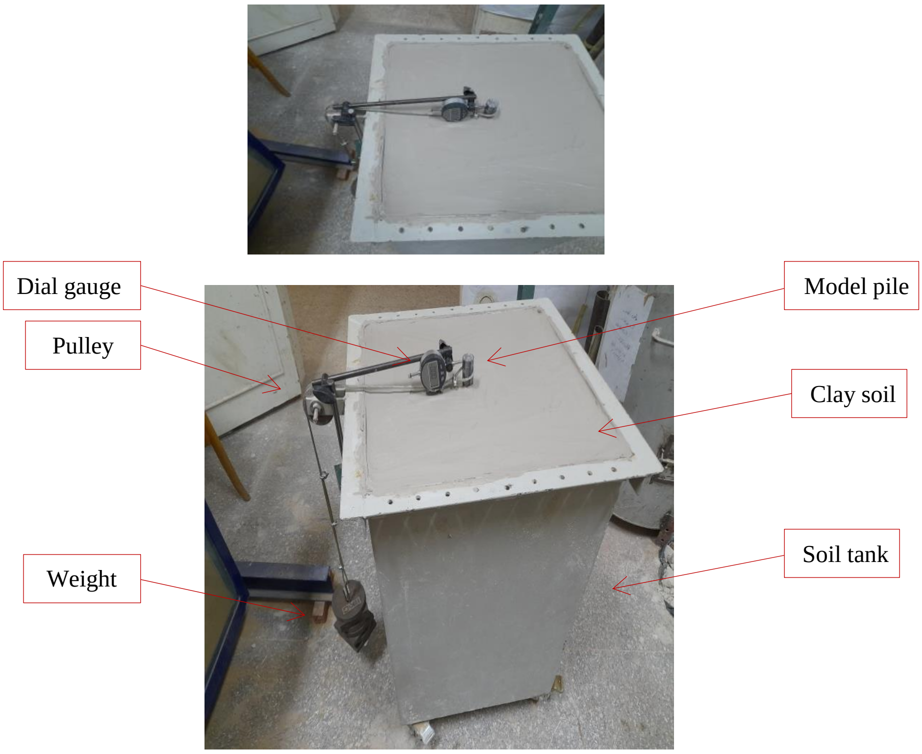


Figure 6. Experimental setup

Afterward, the pile clamp was carefully removed, and the tank surface was leveled with clay before covering it with plastic wrap and allowing it to sit for 24 hours before examination. At the onset of pile load testing, a dial gauge was affixed to the edge of the pile cap and zeroed. Incremental loads were applied to the weight holder, and the reading of the dial gauge was recorded at each load increment. It's noteworthy that by layering the clay randomly, samples were obtained from various depths and positions to ensure uniform shear strength, which was confirmed through direct shear box or vane shear testing to maintain homogeneity across all samples, as reported by Boominathan & Ayothiraman [23].

2.5. Testing Parameters and Research Plan

A testing program was designed and executed to evaluate how variations in pile head geometry, shapes, and enlargement impact the behaviour of piles, specifically focusing on improvements in subgrade reactions. Table 2 presents the data collected from this testing program. Initially, the effect of enlarging pile heads on pile performance was assessed by testing standard piles to establish baseline data for comparison. Subsequent test series were conducted to analyse the performance of enlarged piles under lateral loads in clay with varying un-drained shear strengths (C_u), as detailed in the corresponding table.

Table 2. Experimental testing program and strategy

Series	Constant parameters	Variable parameters	No. of tests
S1	L/D=12, 24 normal piles	Pile slenderness ratios C_{u} = (10 and 15 kPa)	4
S2	L/D_p=12, 24 with an enlarged head L_e= 0.2 L_p	Δ D_e = (0.75, 0.875 and 1) D_p C_{u} = (10 and 15 kPa)	12
S3	L/D_p=12, 24 with an enlarged head L_e= 0.3 L_p	Δ D_e = (0.75, 0.875 and 1) D_p C_{u} = (10 and 15 kPa)	12
S4	L/D_p=12, 24 with an enlarged head L_e= 0.4 L_p	Δ D_e = (0.75, 0.875 and 1) D_p C_{u} = (10 and 15 kPa)	12
S5	L/D_p=12, 24 with a conical head L_e= 0.4 L_p	Δ D_e = (0.75, 0.875 and 1) D_p C_{u} = (10 and 15 kPa)	12

C_u (un-drained shear strength); L_e (head length), L_p (pile length); Δ D_e (enlarged diameter); D_p (pile diameter).

3. Results and Discussion

The tests are categorized into two series of figures for each scenario, depicting the pile behavior with and without enlarged heads for various soft clay cohesion levels. The experimental findings showcase the lateral loads plotted against lateral displacement (P-S) curves for different pile stiffness ratios and enlarged configurations, illustrated in Figures 7 to 12.

The lateral load-deflection response of piles is analyzed using the subgrade reaction method, which treats the pile as a beam on an elastic foundation. In this method, the soil is modeled as a series of closely spaced, independent elastic springs. The "subgrade reaction modulus," which represents the stiffness of these springs, characterizes the elastic soil medium and is defined by the formula K = P/S, where P is the soil resistance and S is the horizontal deflection of the pile according to Winkler [24]. The relationship between pile deformation and soil resistance is depicted by the P-S curve. The subgrade modulus is calculated after reaching the failure load, with horizontal displacement S set at 10% of the pile diameter (D), following Wei [25].

In all test series, the enlarged heads were positioned at the top of the pile and oriented perpendicular to the load, as noted by Peng et al. [26], to enhance lateral capacity through increased pile head diameter. The model test results reveal three main stages in the curves: initial linear, transition, and final linear regions, consistent with findings from Hirany & Kulhawy [27] and Azzam and Basha [28]. The enlargement effect on subgrade modulus is minimal or negligible in the initial two stages but becomes significant in the final linear region, especially under higher applied loads.

Initial investigations focused on the behavior of standard piles at various length-to-diameter (L/D) ratios in the two soil series under lateral loads to establish baseline data. The performance of enlarged piles will be compared to that of standard piles without head enlargement, with further analysis provided to clarify the model test results.

3.1. Effect of Enlarged Length

Three test series were conducted on enlarged piles with L/D_p ratios of 12 and 24, featuring various enlargement depths. Each test included results for different cohesion levels, C_u, of 10 and 15 kPa. Figures 7 and 8 depict the typical relationship between applied lateral load (P) and relative normalized horizontal displacement (S/D) of normal and enlarged head piles embedded at different depths in varying soft clay cohesion. Overall, the load-displacement behaviors for all tested model piles exhibit similar trends. Figure 7 illustrates that for piles with $L/D_p = 24$, $C_u = 15$ kPa, and $\Delta D_e = D_p$, increasing the head depth from 0.2 to 0.4 results in the subgrade modulus increasing by 1.5 to 1.30 times compared to piles without enlargement. Additionally, for $L/D_p = 12$, the subgrade modulus increases by increasing the length until it reaches twice the normal pile value for Le = 0.4 L_p and $\Delta D_e = D_p$. The improvement in subgrade modulus for enlarged head piles can be influenced by both head depth and slenderness ratio. As the L/D_p ratio increases, the degree of improvement in the subgrade modulus of enlarged head piles with $\Delta D_e/D_p = 1.0$ at $L/D_p = 24$ is found to be 2.46 times higher than that of $L/D_p = 12$.

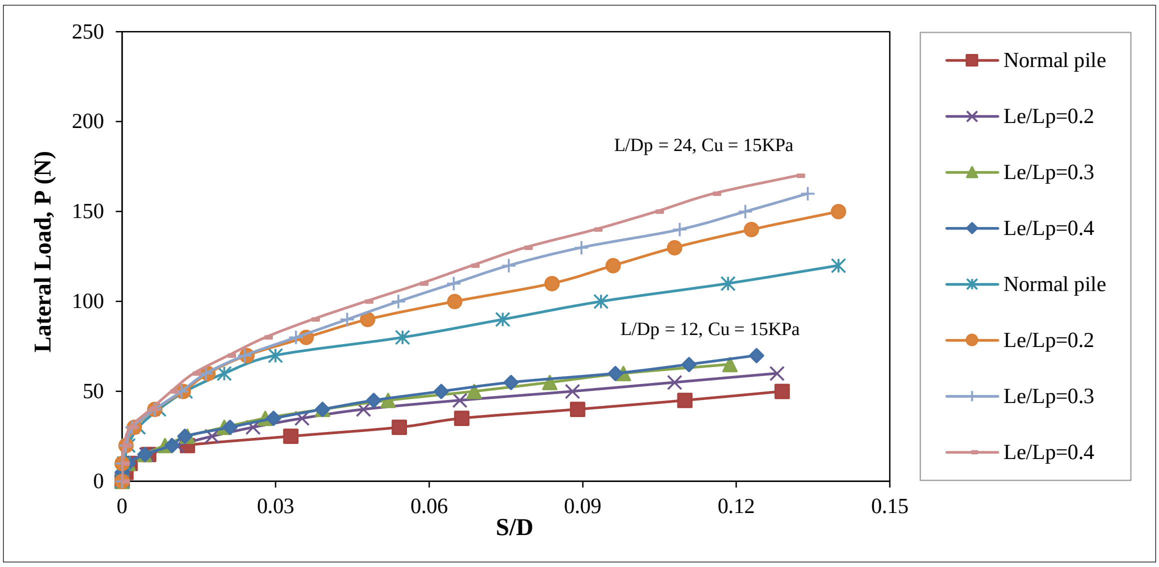


Figure 7. P-S curve for various enlarged lengths (L/D_p = 12 and 24, $\Delta D_e/D_P = 1.0$, and C_u = 15 kPa)

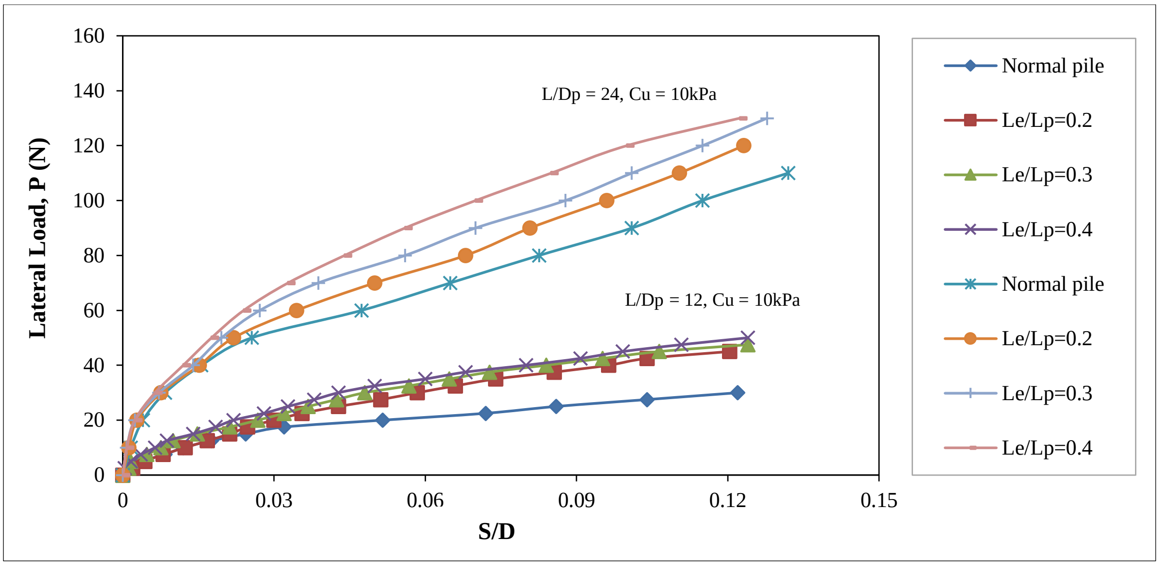


Figure 8. P–S curve for various enlarged lengths (L/D_p = 12 and 24, $\Delta D_e/D_P = 1.0$, and C_u = 10 kPa)

In very soft clay (Figure 8), for L/Dp = 24, increasing the head enlargement depth (Le) from 0.20 to 0.40 Lp results in a notable increase in the subgrade modulus, rising by a factor of 1.10 to 1.30 compared to a normal pile without enlargement. Similarly, for L/Dp = 12, when Le = 0.4 Lp, the subgrade improvement is twice the value of a normal pile's subgrade.

These results emphasize that increasing the enlargement depth improves the subgrade modulus by expanding the effective area at the top of the pile head, enabling it to better resist lateral loading. The increased diameter of the pile provides additional surface area, enhancing the passive resistance behind the pile head.

3.2. Effect of Diameter Enlargement

The effect of head diameter with different values on the subgrade reaction is discussed in this section. The influence of enlargement with different head diameters on laterally loaded piles, specifically the increase in the subgrade soil modulus, was examined and analyzed in comparison with normal piles without enlargement, as shown in Figures 9 and 10. These figures display the load versus settlement ratio at different enlargement geometries, widths, and depths. The results again confirm that using enlarged pile types tends to produce a significant improvement in lateral performance, reflecting a marked enhancement in the subgrade modulus of the pile.

Figure 9 shows that for piles with stiffness (L/Dp = 24, Le/Lp = 0.40, and Cu = 15 kPa), the subgrade modulus increases by as much as 40% and 70% for the cases of Δ De = 0.75 and 0.875 Dp, respectively. In contrast, for an enlarged diameter ratio of Δ De/Dp = 1.0, the improvement in the lateral response is found to be 200% of the regular pile without a head under the same cohesion conditions of 15 kPa. It can be seen that increasing the pile head diameter shows significant progress in lateral resistance for piles with stiffness L/Dp = 12 in the case of Cu = 15 kPa. The subgrade modulus improved by 150%, 175%, and 200% for the cases of Δ De/Dp = 0.75, 0.875, and 1.0, respectively, compared with normal piles.

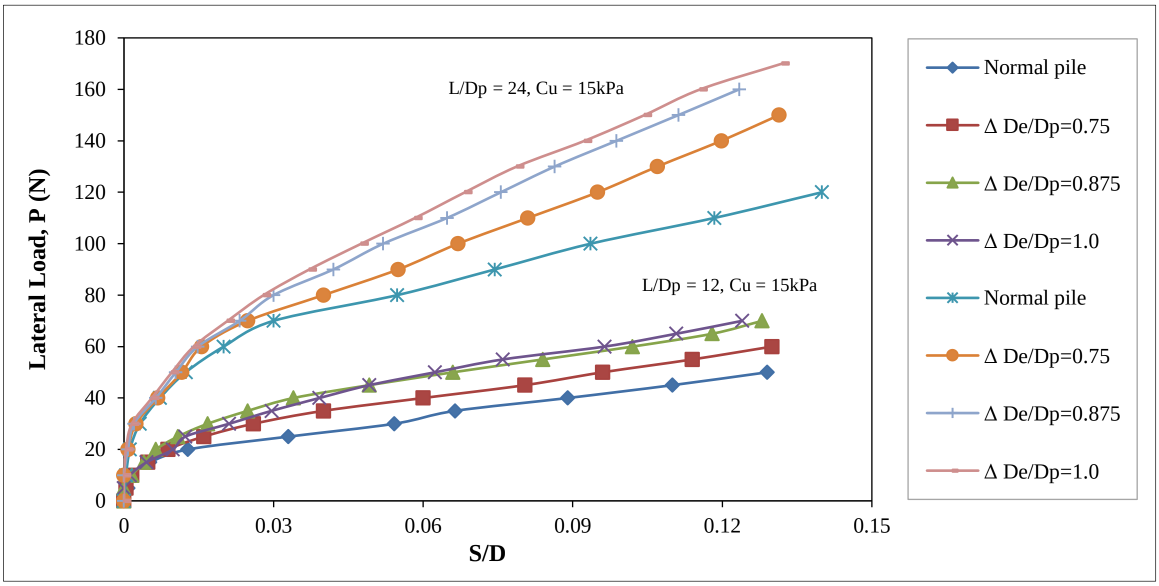


Figure 9. P–S curve for various enlarged diameters (L/D_p = 12 and 24, L_e/L_P =0.4, and C_u = 15 kPa)

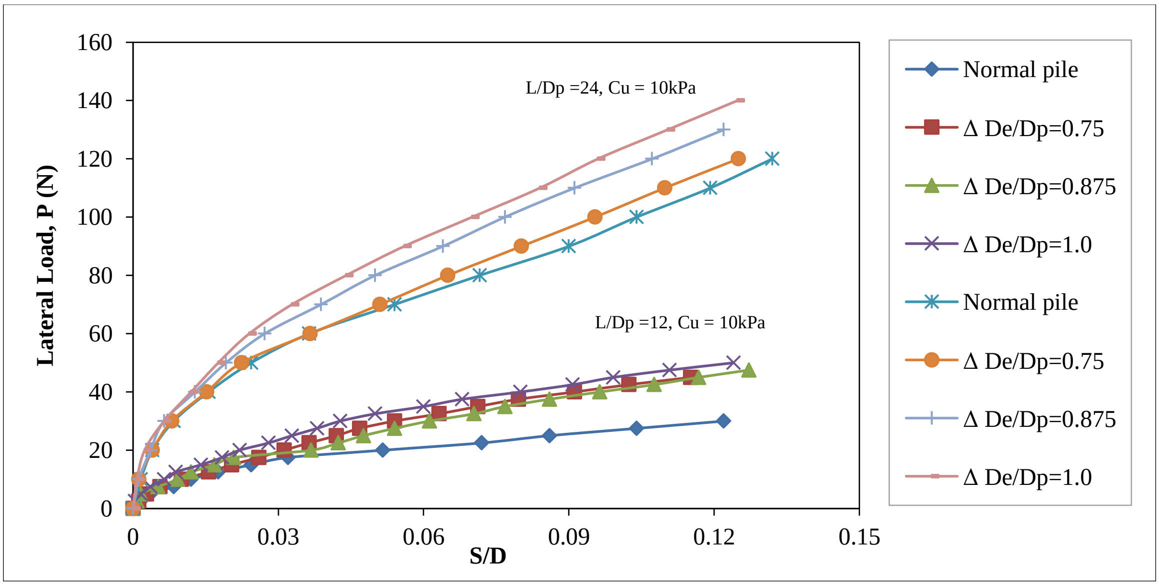


Figure 10. P–S curve for various enlarged diameters (L/D_p = 12 and 24, L_e/L_P =0.4, and C_u = 10 kPa)

Figure 10 shows a remarkable increase in the behavior of the subgrade modulus for piles with stiffness L/Dp = 24 in the case of Cu = 10 kPa when using enlarged piles instead of regular piles, by as much as 120%, 116%, and 130% for the cases of Δ De/Dp = 0.75, 0.875, and 1.0, respectively. The results presented in Figure 10 illustrate that for piles with stiffness L/Dp = 12 and Cu = 10 kPa, the subgrade improvement in the case of Δ De = Dp reaches twice the subgrade value of the normal pile.

This phenomenon can be attributed to the fact that an enlarged pile head increases soil resistance by expanding the area subjected to passive earth pressure behind the enlarged head, significantly enlarging the passive pressure area in front of the pile compared to standard piles. The enlarged pile head effectively creates a stiffer, equivalent head that better supports lateral loads and reduces horizontal displacement of the modified pile in comparison to regular piles.

3.3. Effect of Conical Shape Head

In this part, the impact of using a tapered head shape on enhancing the subgrade clay modulus of modified piles under lateral loads is investigated. Figures 11 and 12 examine the effect of employing a tapered head to increase the subgrade soil modulus. The observed test results demonstrate that incorporating any tapered shape with various geometries in the upper part of the pile head generates additional passive earth resistance against lateral loads, leading to a noticeable increase in the soil subgrade modulus. Figure 11 illustrates the load versus horizontal deformation ratio for enlarged piles with a tapered shape in the case of Le/Lp = 0.40 and L/Dp ratios of 24 and 12, Cu = 15 kPa, for different values of the enlarged diameter Δ De. It was observed that for L/Dp = 24, the subgrade modulus improved by 1.40 and 1.33 times compared to the normal pile under the same conditions for head diameter ratios of Δ De/Dp = 1.0 and 0.75, respectively. Meanwhile, Figure 12 illustrates and confirms that the presence of such a tapered head can significantly enhance the subgrade modulus of embedded piles in very soft clay, though to a lesser extent compared to soft clay with Cu = 15 kPa. The curves presented in Figure 10 for pile stiffness of L/Dp = 24, utilizing the tapered shape, indicate a potential increase in subgrade modulus by as much as 127% and 120% relative to the normal piles for Δ De/Dp = 1.0 and 0.75, respectively. Similarly, these values are found to be 170% and 153% for L/Dp = 12 in the case of very soft clay with the same geometry. Consequently, the obtained results suggest that employing any tapered head shape enhances the subgrade modulus of normal piles. However, uniformly enlarged heads were found to be more practical and effective than tapered shapes due to their feasibility.

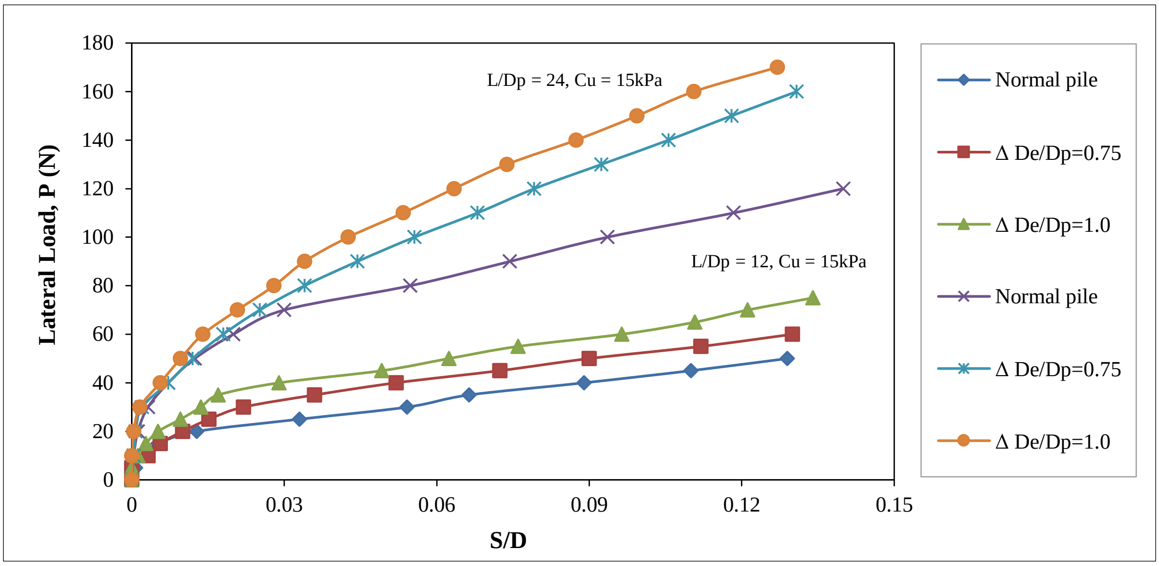


Figure 11. P–S curve for various tapered diameters (L/D = 12 and 24, L_e/L_P =0.4, and C_u = 15 kPa)

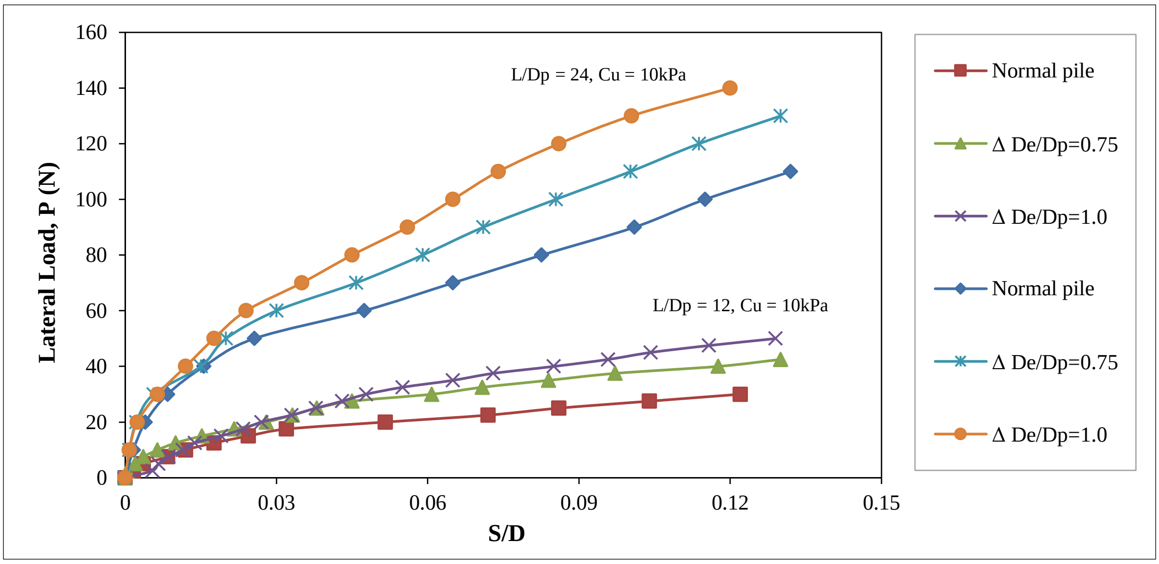


Figure 12. P–S curve for various tapered diameters (L/D = 12 and 24, L_e/L_P =0.4, and C_u = 10 kPa)

4. Finite Element Modeling

This paper compares the performance of traditional and enlarged piles, demonstrating how enlargement affects pile behavior under lateral loads in clay soil. The software PLAXIS 3D V20, a well-known finite element method (FEM) tool, simulates complex, non-linear pile interactions. The analysis of soil-pile interaction involves two main procedures. The first procedure calculates the initial stresses within the soil mass using its weight and the at-rest pressure K_0 technique. Prior to constructing the enlarged pile, this procedure is performed in an undrained state. In the second stage, to ensure that all displacements are attributed to external loads, all movements are set to zero before pile installation begins.

The soil volume and piled foundation were represented using a 10-tetrahedral element. In this numerical study, the soil behavior is governed by the Hardening Soil Model (HSM), as shown in Figure 13. The global mesh coarseness was set to "fine" to ensure accurate analysis for this study. The hardening soil model is an advanced model that provides realistic soil responses, accounting for nonlinearity, stress dependency, and inelasticity [29]. PLAXIS 3D V20 automatically applies a set of general boundary fixities to the geometry model.

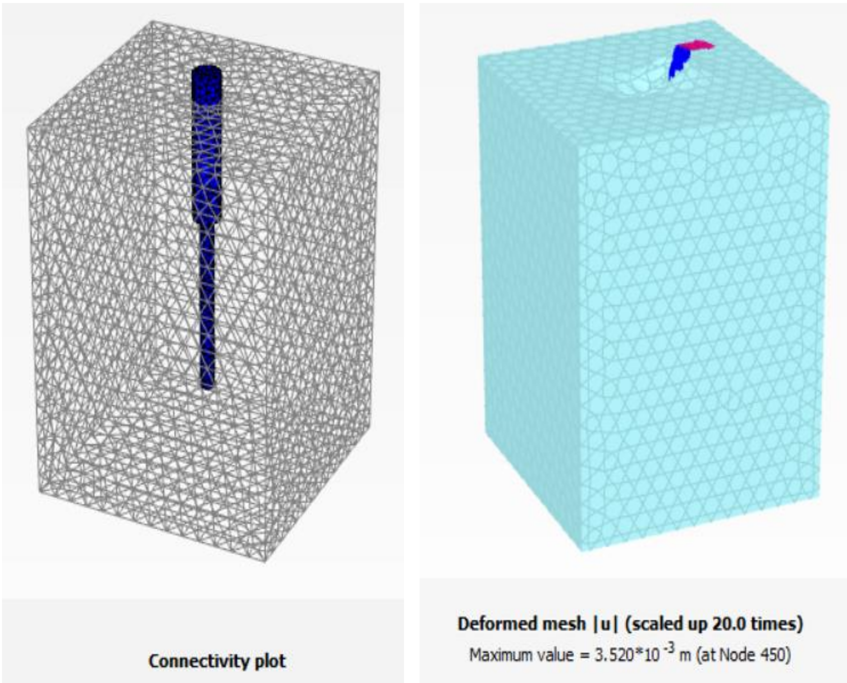


Figure 13. Soil model and deformed meshes

To establish these circumstances, the following rules were followed to: The bounds of the vertical model are fixed in the x-direction (ux = 0), free in the y- and z-directions, and parallel to the yz-plane. The vertical model bounds are also free in the x- and z-directions and fixed in the y-direction (uy = 0) when the normal in the y-direction (i.e., parallel to the xz-plane) is used.

The bounds of the vertical model are fixed in the x and y directions (ux = uy = 0) and free in the z direction; neither direction is their normal. The bottom border of the model is fixed for all directions (uz = ux = uy = 0). The ground surface is free in every direction (PLAXIS 3D MANUAL).

The design steps using PLAXIS 3D V20 are shown in the following:

- Constructing the model's geometry.
- Definition of material properties (pile and soil).
- Mesh generation.
- Staged construction: (Initial stage; Installation stage; Loading conditions stage; The final stage is the calculation stage).

HSM was described in the Zidan & Ramadan [30]. Several soil properties are assumed to define HSM for clay soil, as shown in Table 3. Using the range of data for Es, the secant Young's modulus (E_{50}^{ref}) of 600 kN/m² was selected [31]. Since an undrained response was assumed during the load test, the Poisson's ratio for the clay soil was set to 0.5. Other factors include the oedometer modulus (E_{oed}^{red}), the unloading-reloading modulus (E_{ur}^{ref}), the interface reduction factor (R_{int}), and the effective cohesion parameter (c').

To reduce the impact of mesh reliance, better mesh is also used in the vicinity of the pile. The thin layer of an interface element is modeled to permit relative mobility between the pile and the ground. As a result, the soil quality reduction factor, R_{int}, is 0.5 [32], which is suitable for friction between clay and concrete. It is also assumed that the steel tube pile has a unit weight (γs) of 78.5 KN/m^2, a Poisson's ratio (**ν**) of 0.3, and a Young's modulus (Es) of 210*10^6 KN/m^2.

This model's details are shown in Table 3. It is significant to mention that PLAXIS 3D was used to examine one set of data (see Table 4). Thus, a set of investigated parameters for piles with Le/Dp = 12 and 24 and Cu = 10 kPa are presented. The findings of laboratory tests were found to match the analysis results (Figure 14), confirming the usage of PLAXIS 3D V20 for this investigation.

Table 3. HSM parameter for very soft clay based on test results and Zhou et al., 2021 [32]

Soil Type	Soil Model	γ (KN/m³)	C_u (KN/m²)	$E_{50}^{ref} = E_{oed}^{red}$ (KN/m²)	$E_{ur}^{ref} = 3\,E_{50}^{ref}$	ν	R_{int}
Very soft clay	HSM	17.5	10	600	1800	0.5	0.5

Table 4. The studied parameters and series

FEM Series	Constant parameters	Variable parameters	No. of tests
S1	C_u =10 KPa, Δ D_e/D_p = 1.0	L_e/L_p = No enlarge, 0.2, 0.3, and 0.4 L_p/D_p = 12	4
S2	C_u =10 KPa, Δ D_e/D_p = 1.0	L_e/L_p = No enlarge, 0.2, 0.3, and 0.4 L_p/D_p = 24	4

4.1. Numerical Results

Figure 14 illustrates the P-S curve for experimental and numerical results, with specific parameters (L/D = 12, Δ D_e/D_p = 1.0, and Cu = 10 kPa). A close match is evident between the experimental and numerical data, indicating a consistent trend. This alignment reinforces the importance of employing an enlarged head to enhance the lateral subgrade resistance of soft clay. However, it's important to note that the bending moment in the pile increases as the pile goes deeper. Figures 15 to 17 illustrate the highest bending moment concentrated at the point where the pile diameter changes

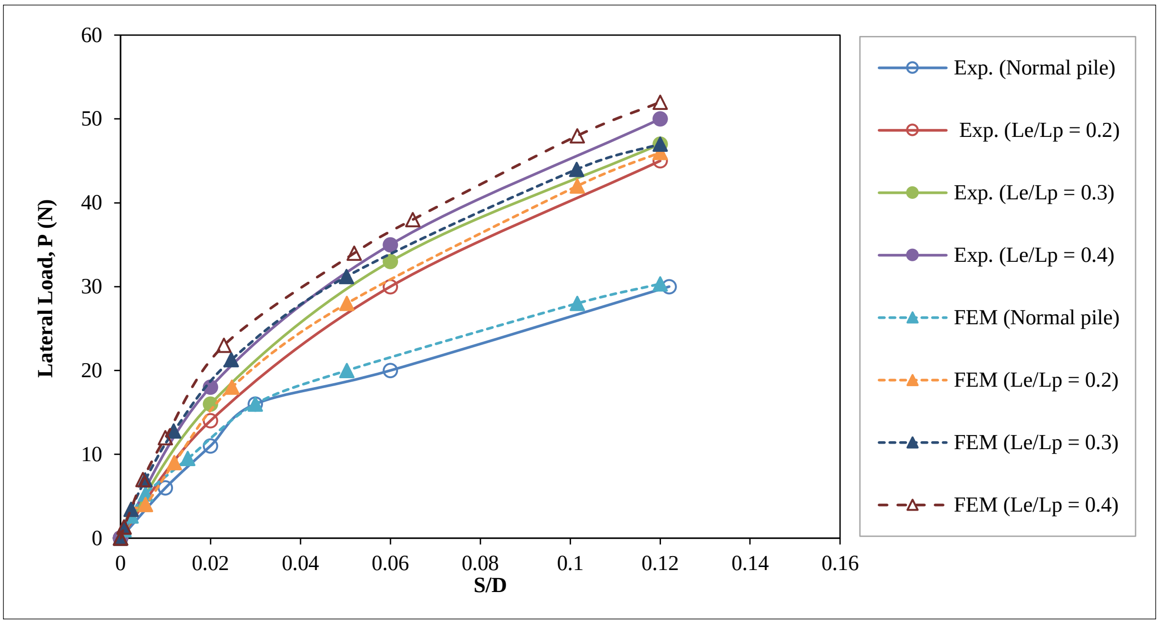
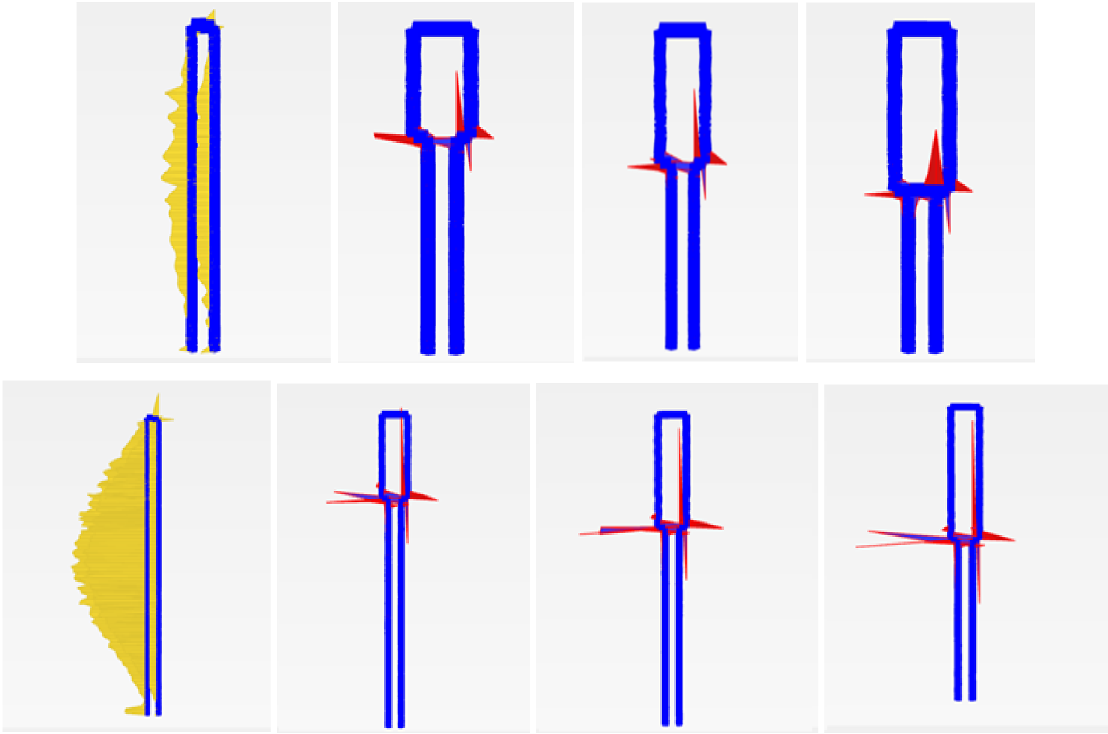


Figure 14. P–S curve for experimental and numerical results (L/D = 12, Δ D_e/D_p = 1.0, and C_u = 10 kPa)

This critical increase in bending moment at the connection zone can be addressed by creating a gradual change in diameter. This smoother transition can reduce the bending moment at the connection by about 95% times the bending moment (BM) with minimal impact on improvement in lateral resistance (lateral enhancement ratio). It can be shown and confirmed in Figure 16.

(a)

(b)



Normal pile Le/Lp = 0.2 Le/Lp = 0.3 Le/Lp = 0.4

Figure 15. The bending moment diagram: (a) L/D$_p$ = 12; (b) L/D$_p$ = 24

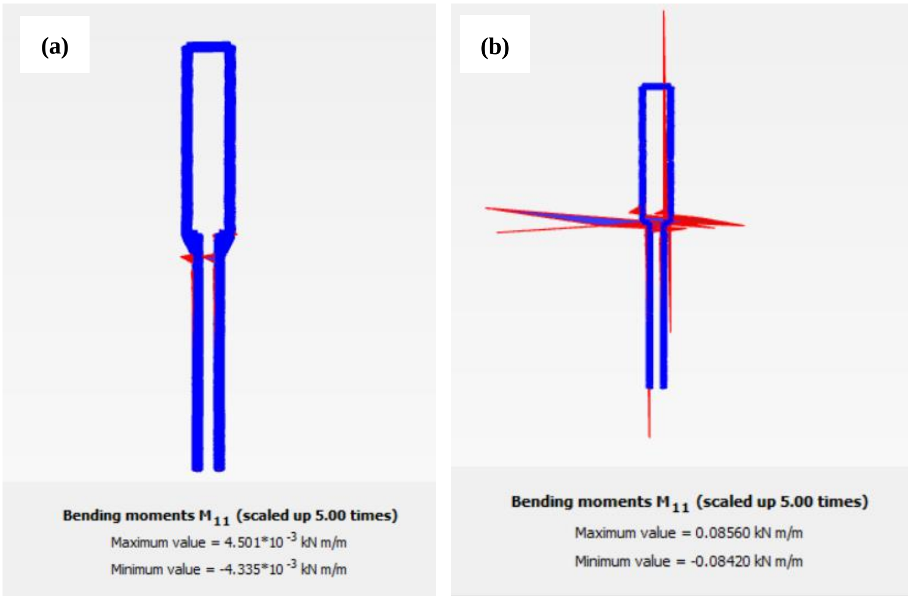


Figure 16. The bending moment diagram: (a) gradual diameter change; (b) sudden diameter change

The effect of an increased pile head on the bending moment under lateral loads in soft clay can be summarized based on numerical results as follows: The bending moment experienced by the pile under lateral pressures in soft clay is influenced by the increase in the pile head diameter, which expands its top section. By distributing the load over a larger area, this enlargement increases lateral resistance, allowing the pile to withstand higher lateral stresses with less deflection. As in Figure 15, this enhanced resistance is crucial for structures subjected to earthquake, wind, or wave forces.

However, increasing the pile head also results in a larger bending moment. While the enlarged head enhances lateral resistance, it also creates a geometric discontinuity that concentrates the bending moment at the point where the enlarged head meets the pile shaft. This concentrated bending moment increases with greater embedment depth, as shown in Figure 15. Such concentration may lead to potential structural weaknesses in the pile.

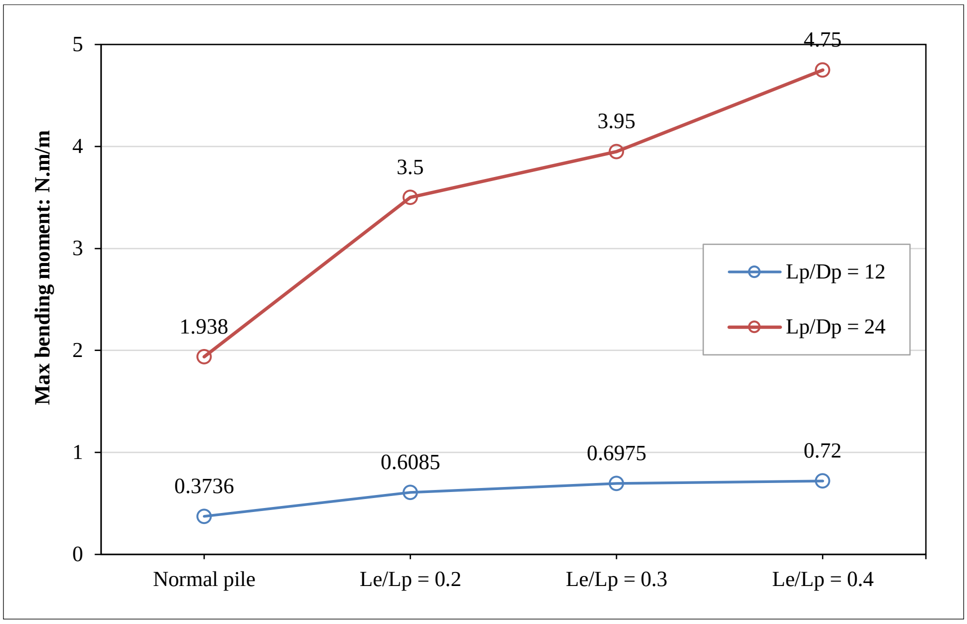


Figure 17. The maximum bending moment induced at different (L_e/L_p) ratios for L_p/D_p = 12 and 24

Research indicates that a gradual change in diameter can effectively mitigate the induced bending moment. Therefore, to reduce the increased bending moment at the connection zone, a gradual transition in diameter can be employed. This smoother transition helps to diminish stress concentration, consequently reducing the bending moment at the connection point. Achieving this involves tapering the pile shaft toward the enlarged head, as shown in Figure 16.

There exists a trade-off between maximizing lateral resistance and minimizing the bending moment. While a larger head enhances resistance, it also intensifies the challenge posed by the bending moment. Implementing a gradual diameter change can mitigate the bending moment but might marginally diminish the overall enhancement in lateral resistance. Based on Figure 17, it is evident that the enlargement of the pile head is influenced by its geometry, specifically the head depth and pile length. As the pile length increases, there is a corresponding increase in the induced lateral load, consequently leading to an increase in the resultant moment. Notably, increasing the head depth also results in a distinct rise in the resulting moment, with a noticeable escalation observed at L_p/D_p = 12. However, a significant increase, characterized by remarkable values, is achieved, particularly when L_p/D_p = 24.

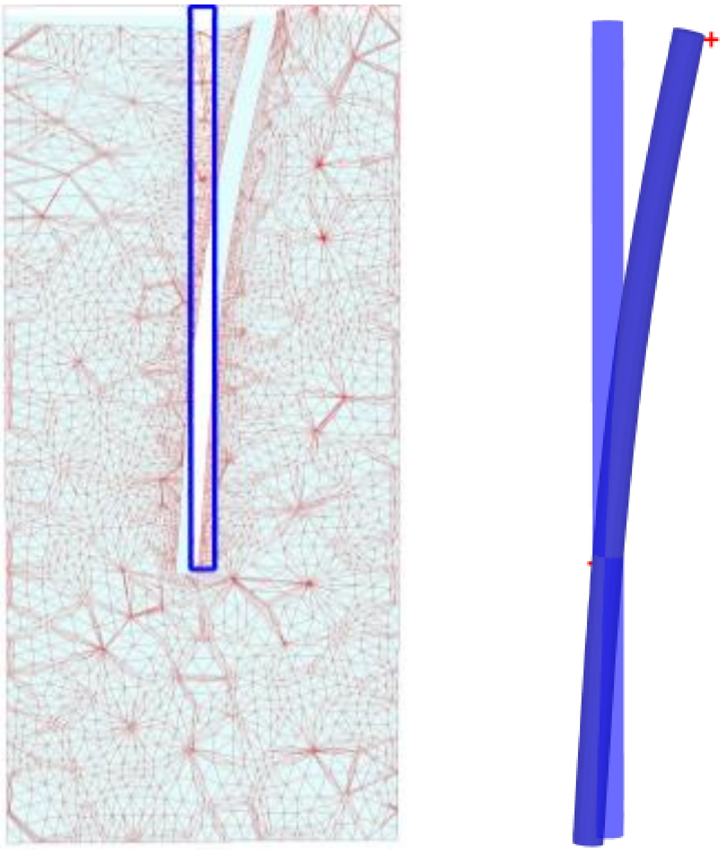
4.2. Soil-Pile Interaction

The process by which the pile and the surrounding soil cooperate to resist lateral loads is known as soil-pile interaction. This nonlinear relationship is influenced by the strength and stiffness of both the pile and the soil. The behavior of a soil-pile system under lateral loads at or above the ground surface depends on several factors.

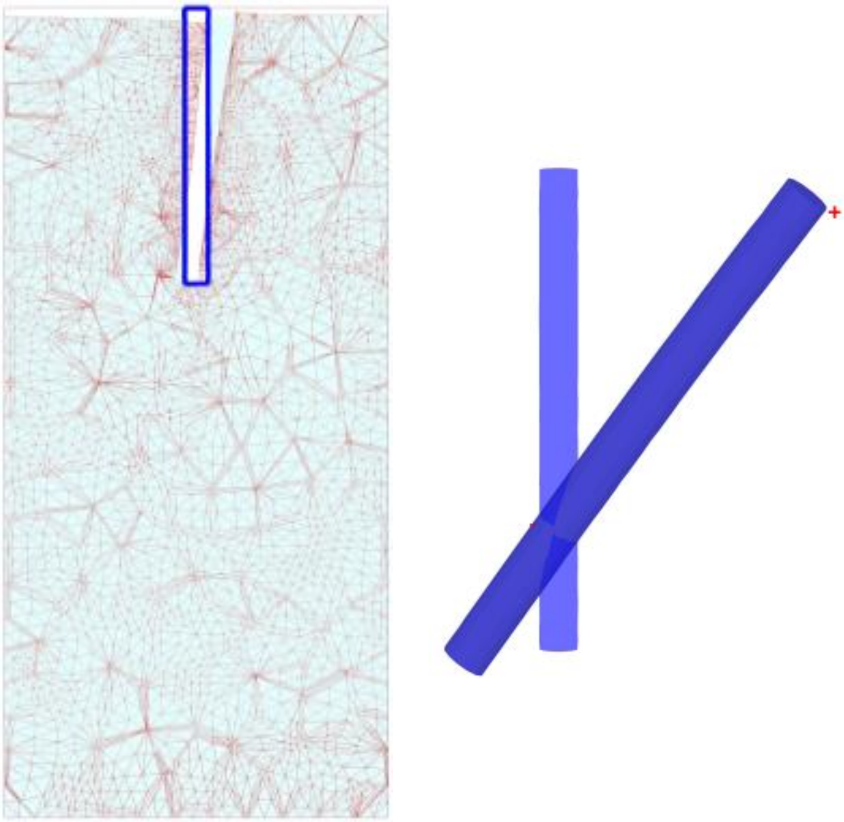
4.2.1. The Flexural Rigidity and Pile Behavior

A pile's flexural stiffness has a major impact on its capacity to tolerate bending under applied loads. Flexible piles can disperse loads deep into the soil because of their increased bending capacity and decreased flexural rigidity. This behavior, however, may lead to bending failure, a particular kind of failure that is commonly observed in long piles.

The relationship between pile length, flexibility, and the probability of this failure mechanism is demonstrated in Figure 18-a, which clearly depicts bending failure in long piles. On the other hand, shear failure is a distinct type of failure that is commonly encountered by short piles. With resistance primarily concentrated in the upper soil layers, short piles rotate as a single, rigid unit. Figure 18-b illustrates how shear failure may result from this behavior.



(a) Long pile



(b) Short pile

Figure 18. Piles deformation

4.2.2. The Impact of Pile Enlargement on Performance

Figures 19-a to 19-d compares enlarged and traditional piles of varying lengths to show how the larger section and pile length impact the pile's performance in clay soil.

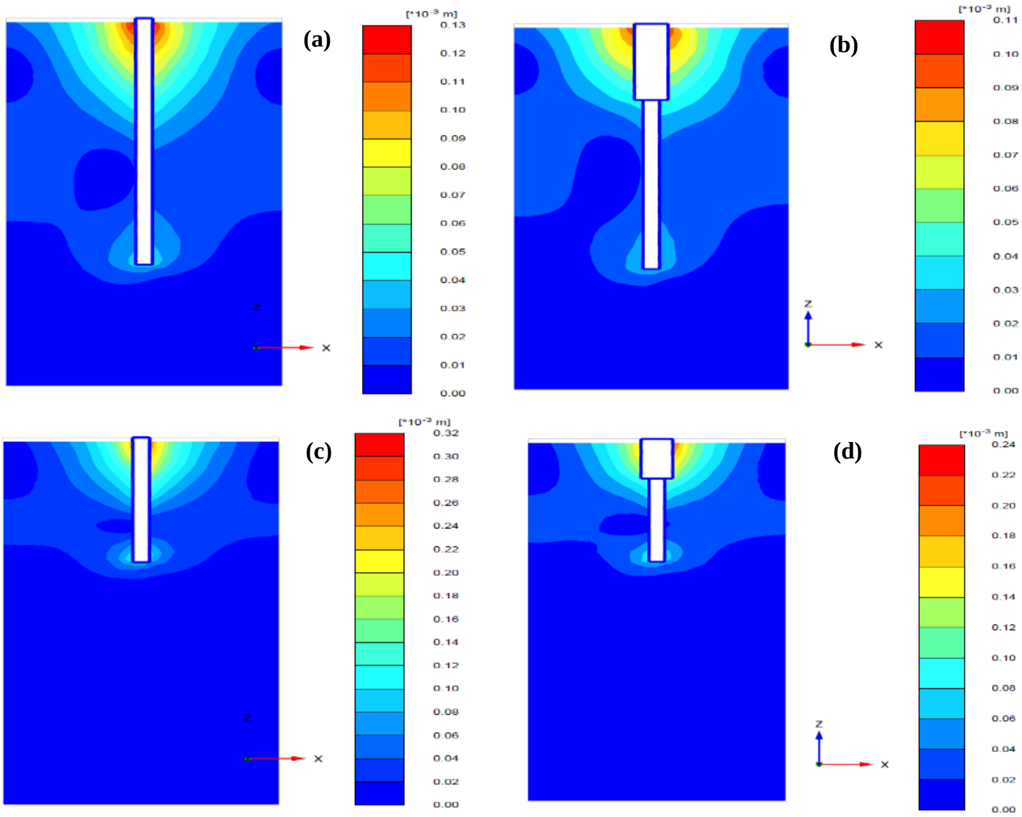


Figure 19. Lateral displacement of the pile: (a) Traditional long pile; (b) Enlarged long pile; (c) Traditional short pile; (d) Enlarged short pile

The Enlarged Section's Effect:

The lateral displacement of the pile reduces from 0.13×10^{-3} m for the conventional pile with L/D = 24 to 0.11×10^{-3} m for the enlarged pile with L/D = 24 and Le/Lp = 0.3 under the same loading circumstances, as illustrated in Figures 19-a and 19-b.

Additionally, Figures 19-c and 19-d demonstrates that, under identical loading circumstances, the lateral displacement of the enlarged pile with the same slenderness ratio and Le/Lp = 0.3 is 0.24×10^{-3} m, while the lateral displacement of the conventional pile with a slenderness ratio of L/D = 12 is 0.32×10^{-3} m.

It can be deduced that the enlarged portion reduces lateral displacement and increases the pile's lateral resistance. The improved effectiveness of the pile is due to the higher skin friction and passive resistance of the enlarged pile, both of which are enhanced by the larger diameter and increased surface area exposed to the soil.

The Pile Length Effect:

When comparing a longer pile with a slenderness ratio of L/D = 24 to a shorter pile with a slenderness ratio of L/D = 12, in both the conventional and enlarged section pile cases, the figures show a decrease in lateral displacement. The longer the pile is, the greater the interaction between the pile and the soil. As a result, the longer pile is more stable against lateral loads. It is clear from the study of using an enlarged head pile under lateral pressure in clayey soil that this approach significantly improves the pile's performance and reduces the possibility of excessive settlement or failure. The enlarged head reduces the influence of lateral pressures and the concentration of stresses that could cause soil failure by distributing lateral loads more evenly over a larger surface area of the clay.

This approach also improves the interaction between the surrounding soil and the pile as the pile responds more effectively to lateral loads due to the more uniform distribution of stress. In addition, the findings demonstrated that variations in the subgrade reaction (K) related to the clay's undrained shear strength and the pile's slenderness ratios significantly impact the pile's overall performance. Furthermore, the experimental models were confirmed through the use of finite element analysis, which offered accurate insights into bending moments and deformation responses that might not be fully recorded by laboratory tests alone. A comparison of the current study's findings with those of earlier research is presented in Table 5.

Table 5. Comparing the present study to previous studies

Study	Previous studies	Methodology	Present study	Comparison / Analysis
Qin et al. [2]	Conducted extensive field and laboratory testing to examine the reaction of finned piles in sand under lateral stress.	Experimental study	Laboratory tests were investigated to evaluate the enhancement of the subgrade modulus for laterally loaded piles with enlarged heads in clay.	The current study emphasizes that adding an enlarged head with a sufficient diameter can significantly improve the lateral subgrade reaction.
Hariswaran et al. [5]	Used finite element analysis to investigate the behavior of the laterally loaded defective (necking) pile with fins surrounding the pile.	Parametric study	Using the numerical program Plaxis 3D, the study was extended by simulating monopiles with and without head enlargements to confirm the experimental findings.	The current study confirms that the pile's configuration affects the extent of lateral capacity enhancement.
Sallam et al. [7]	Investigated those lateral stresses affected finned shaft piles in sandy soil.	Experimental study	The influence of enlargement with different head diameters on laterally loaded piles, to mention the increase in the subgrade soil modulus, was examined and analysed in comparison with normal piles without enlargement.	The present study confirms that the efficiency of lateral capacities of enlarged piles improves with the increase in width/pile diameter ratios (Δ De/Dp).
Islam et al. [4]	Investigated that the failure mechanism and lateral response of a single pile in soil modified with cement.	Numerical analysis	The influence of enlargement with different depths on laterally loaded piles.	The present study confirms that the improvement in subgrade modulus for enlarged head piles can be influenced by both head depth and slenderness ratio.

The existing literature primarily concentrates on experimental and numerical approaches to improve the lateral load-bearing capacity of piles, often neglecting the effect of these methods on the subgrade reaction around the pile head. This paper seeks to define, establish, and assess the connection between subgrade modifications and different configurations of enlarged piles. More specifically, the study examines the variations and enhancements in the soil subgrade reaction "K" about the undrained shear strength of the clay and the slenderness ratio of the model piles, considering both piles with and without enlarged heads.

Finally, the capacity of the enlarged head approach to enhance the pile's structural performance and mitigate possible hazards such as excessive settlement or failure makes it feasible and cost-effective to use in actual projects. The overall cost of an enlarged head pile is usually higher than that of a conventional pile; however, the additional benefits may justify the increased expenditure. Additional materials are needed for the increased head pile, which needs more steel or concrete to produce a greater surface area. Initial costs of production and installation are raised by this extra material.

Furthermore, the complexity of installation, particularly when dealing with the specific requirements of soft clay or challenging soil conditions, may require the use of specialized equipment and additional labor hours during the construction process for the enlarged head pile. However, despite the higher initial costs, the benefits of better load distribution, reduced settlement risk, and improved stability in weak soils make it a viable and efficient alternative for certain projects.

The traditional pile, on the other hand, normally has lower initial costs because it requires fewer materials and specialized equipment due to smaller cross-sections. Nevertheless, the conventional pile might not provide the same degree of load distribution, which might eventually result in problems like excessive settlement or failure in poorer soils.

Despite the higher initial cost, the enlarged head pile offers several advantages that justify the expenditure. Its increased surface area facilitates better load distribution, enhances the interaction between the pile and the surrounding soil, and reduces the risk of failure. Over time, this can eliminate the need for costly maintenance, repairs, or replacements often associated with traditional piles. Therefore, in applications requiring higher load-bearing capacity and long-term stability in weak soil conditions, the enlarged head pile can be considered a more cost-effective solution when factoring in all aspects of cost, including performance and durability.

5. Conclusions

A laboratory model study was carried out to improve the horizontal subgrade reaction of piles by altering the pile head at the top of the applied load using an enlarged head technique with different geometries. The findings show a significant increase in the pile's horizontal subgrade reaction due to the enlarged head. From the detailed experimental model study on the modified piles, the following key conclusions can be drawn:

- The subgrade horizontal reaction modulus in soft clay is highly affected by pile stiffness, soft clay cohesion, and enlargement geometry.
- To increase the subgrade modulus of piles in soft clay, it is recommended to use the head geometry with a diameter of two piles and a depth equal to 0.4 pile lengths.

- The addition of an enlarged head with sufficient depth can significantly improve the lateral subgrade reaction. For piles $L_p/D_p = 24$ with an enlarged head pile of ($L_e/L_p = 0.4$, $\Delta D_e/D_P = 1.0$, and $C_u = 15$ kPa), the subgrade modulus improvement is found to be 200% of a normal pile.
- For enlarged head piles in very soft clay at ($L_e/L_p = 0.4$, $\Delta D_e/D_P = 1.0$, and $C_u = 10$ kPa), the improvement in the subgrade capacity becomes 1.3 and 2 times that of a normal pile.
- As the ratio L/D_p increases, the degree of improvement in the subgrade modulus of the enlarged head pile with $\Delta D_e/D_p = 1.0$ at $L/D_p = 24$ is found to be higher by 2.46 of its value at $L/D_p = 12$.
- Utilizing tapered enlarged heads improved the subgrade modulus by 1.40 times for piles in soft clay ($C_u = 15$ KPa, $L/D_p = 24$, and $\Delta D_e/D_p = 1.0$), while this increase was as much as 1.33 for enlarged piles at $\Delta D_e/D_p = 0.75$ in the case of very soft clay.
- In comparison between the uniformly enlarged and tapered heads at the same head depth ($L_e/L_p = 0.40$) and head diameter in soft clay cohesion of 15 kPa, the uniform pile head is higher than the tapered head by as much as 15% ($L/D_p = 24$).
- Utilizing the tapered can increase the subgrade by as much as 127% and 120% relative to normal piles for $L_p/D_p = 24$, $\Delta D_e/D_p = 1.0$, and 0.75 in that order. At the same time, these values were found to be 170 and 153% for $L/D_p = 12$ in the case of very soft clay with the same geometry.
- The results confirmed that using any shape of tapered head significantly improves the subgrade modulus of the normal pile. But the uniformly enlarged head was more practical and effective than the tapered shape due to its feasibility.
- The numerical findings validated the experimental model test, offering deeper insights into deformation response and bending moment dynamics that elude laboratory experiments. Additionally, they underscore the efficacy of enlarging the pile head as a strategic approach to bolstering lateral resistance in soft clay soils. Nevertheless, it's imperative to account for the consequent rise in bending moment at the connection zone. Implementing a gradual diameter change emerges as a viable solution to attenuate this drawback while preserving a harmonious equilibrium between heightened lateral capacity and diminished bending moment.

6. Declarations

6.1. Author Contributions

Conceptualization, M.E. and E.K.; methodology, W.A., M.E., and E.K.; software, E.K.; validation, E.K. and M.E.; formal analysis, E.K.; investigation, E.K.; resources, M.E.; data curation, M.E.; writing—original draft preparation, E.K.; writing—review and editing, M.E.; visualization, W.A.; supervision, W.A. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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